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THE LACK OF VERY ULTRALUMINOUS X-RAY SOURCES IN EARLY-TYPE GALAXIES

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ABSTRACT

We have searched for ultraluminous X-ray sources (ULXs) in a sample of 28 elliptical and S0 galaxies observed with *Chandra*. We find that the number of X-ray sources detected at a flux level that would correspond to a 0.3–10 keV X-ray luminosity of $\sim 2 \times 10^{39}$ ergs s^{-1} or greater (for which we have used the designation very ultraluminous X-ray sources; VULXs) at the distance of each galaxy is equal to the number of expected foreground/background objects. In addition, the VULXs are uniformly distributed over the *Chandra* field of view rather than distributed like the optical light of the galaxies, strengthening the argument that the high flux sources are unassociated with the galaxies. We have also taken the VULX candidate list of Colbert and Ptak and determined the spatial distribution of VULXs in early-type galaxies and late-type galaxies separately. While the spiral galaxy VULXs are clearly concentrated toward the centers of the galaxies, the early-type galaxy VULXs are distributed randomly over the *ROSAT* HRI field of view, again indicating that they are not associated with the galaxies themselves. We conclude that with the exception of two rare high luminosity objects within globular clusters of the elliptical galaxy NGC 1399, VULXs are generally not found within old stellar systems. However, we do find a significant population of sources with luminosities of $1 - 2 \times 10^{39}$ ergs s^{-1} that reside within the sample galaxies that can be explained by accretion onto 10–20 M$_\odot$ black holes. Given our results, we propose that ULXs be defined as X-ray sources with L_X(0.3–10 keV) $> 2 \times 10^{39}$ ergs s^{-1}.

Subject headings: binaries: close—galaxies: elliptical and lenticular, cD— X-rays: binaries—X-rays: galaxies

1. INTRODUCTION

The existence of very luminous X-ray point sources located within galaxies but not coincident with the galaxy's nucleus has spawned a flurry of investigations into the nature of these objects in recent years. Usually defined as having an X-ray luminosity exceeding 10^{39} ergs s^{-1}, these ultraluminous X-ray objects (ULXs) were originally discovered in the *Einstein* era (Fabbiano 1989), and studied further with *ROSAT* and *ASCA* (e.g., Colbert & Ptak 2002; Makishima et al. 2000; Roberts & Warwick 2000). The excellent spatial resolution of *Chandra* has led to the discovery of many more ULXs densely packed within star-forming regions of interacting galaxies such as the Antennae (Zezas & Fabbiano 2002).

While a few ULXs have been identified with supernovae, the majority of ULXs are thought to be accreting objects owing to the fact that their X-ray flux can vary significantly over timescales of months and years. The X-ray luminosities of ULXs can exceed the Eddington luminosity of a 1.4 M$_\odot$ neutron star by up to two orders of magnitudes, calling into question the physical nature of these sources. One possible explanation set forth to explain the origin of ULXs are intermediate mass (50–1000 M$_\odot$) black holes accreting at or near their Eddington limit (Colbert & Mushotzky 1999). Such a population of intermediate mass black holes would represent a missing link between stellar-mass black holes like those found in the Milky Way and supermassive black holes at the centers of galaxies. However, it is uncertain how a black hole in this mass range can form, and arguments both for (Miller & Coleman 2002; Miller et al. 2003) and against (King et al. 2001; Roberts et al. 2002; Begelman 2002) this scenario have been presented previously. Another possible explanation is that ULXs are normal accreting low-mass black holes for which the X-ray emission is beamed toward us (King et al. 2001). In such a model, King et al. (2001) proposed that the most likely candidate in a beaming scenario is a phase of thermal time scale mass transfer in binaries with intermediate or high mass donor stars. The need for an intermediate or high mass donor star naturally explains the tendency for ULXs to be found within galaxies with recent strong star-formation.

Such a beaming scenario would argue that ULXs should not be found within old stellar populations such as S0 and elliptical galaxies. However, a recent compilation of ULX candidates in nearby galaxies by Colbert & Ptak (2002) found 34 ULX candidates within a sample of 15 elliptical and S0 galaxies. While Colbert & Ptak (2002) caution that some of the ULX candidates might be unrelated foreground/background objects, the extent to which contamination from unrelated sources might affect the ULX rate within early-type galaxies was not determined. Indeed, Irwin, Athey, & Bregman (2003) found that the number of very high X-ray flux sources within a sample of 13 elliptical and S0 galaxies observed with *Chandra* was exactly that expected from contaminating foreground/background sources. While there was an overabundance of sources with X-ray luminosities in the $1 - 2 \times 10^{39}$ ergs s^{-1} luminosity range, the number of sources with apparent luminosities exceeding 2×10^{39} ergs s^{-1} in the 13 galaxies was exactly what was expected from foreground/background objects.

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Table 1
Sample of Galaxies

Galaxy	Obs. ID	Distance (Mpc)	Galaxy	Obs. ID	Distance (Mpc)	Galaxy	Obs. ID	Distance (Mpc)
NGC 1316	2022	21.5	NGC 3923	1563	22.9	NGC 4494	2079	17.1
NGC 1332	4372	22.9	NGC 4125	2071	23.9	NGC 4552	2072	15.4
NGC 1399	319	20.0	NGC 4261	834	31.6	NGC 4621	2068	18.3
NGC 1404	2942	21.0	NGC 4365	2015	20.4	NGC 4636	323	14.7
NGC 1549	2077	19.7	NGC 4374	803	18.4	NGC 4649	785	16.8
NGC 1553	783	18.5	NGC 4382	2016	18.5	NGC 4697	784	11.8
NGC 3115	2040	9.7	NGC 4406	318	17.1	NGC 5846	788	24.9
NGC 3377	2934	11.2	NGC 4459	2927	16.1	IC 1459	2196	29.2
NGC 3379	1587	10.6	NGC 4472	321	16.3			
NGC 3585	2078	20.0	NGC 4486	2707	16.1			

Still, only ten very high X-ray flux sources in the sample of 13 galaxies limited the strength of the claim that early-type systems do not generally harbor very luminous ULXs. In this *Letter* we present data from a larger sample of galaxies observed with *Chandra* to verify that very luminous ULXs (VULXs), defined as sources with 0.3–10 keV luminosities exceeding 2×10^{39} ergs s^{-1}, are absent from elliptical and S0 galaxies.

2. OBSERVATIONS AND DATA REDUCTION

For our sample we began with all elliptical and S0 galaxies that were available in the *Chandra* archive as of October 2003 for which the galaxy was observed with the S3 chip of the ACIS detector. We have only included galaxies such that a 10^{39} ergs s^{-1} source would contain at least 36 source counts (or four times the standard detection limit) so that incompleteness would not be an issue. This limited us to galaxies within $\sim$ 35 Mpc for a typical *Chandra* observation. We excluded the very nearby early-type galaxies NGC 5102 and NGC 5128 for which a visual inspection of the images revealed no high flux sources, and for which the expected number of foreground/background high flux sources was too small to make their addition to the sample worthwhile. These criteria led to a sample of 30 galaxies.

Determining an accurate distance to each galaxy is crucial if we hope to ascertain whether sources more luminous that a certain limit are present in the sample or not. We have chosen to use the I-band surface brightness fluctuation distances (I-SBF) of Tonry et al. (2001), since this study provides the largest homogeneously-analyzed sample of all the distance estimator methods, and includes all 30 galaxies in our sample. For each galaxy, we searched for an independent estimate of the distance, typically from the globular cluster luminosity function method or the K-band surface brightness fluctuation method, and in general found good agreement. Two exceptions were NGC 1407 and NGC 720, for which the I-SBF distances were 60% and 30% larger than other distance estimators, respectively (Perrett et al. 1997; Mei et al. 2001). Given the large uncertainties to these galaxies, we have excluded them for our sample. For the other galaxies we have assumed the I-SBF distances, which are consistent with distances derived from other methods at the 15% level. The 28 galaxies are listed in Table 1.

The galaxies were processed in a uniform manner following the *Chandra* data reduction threads. The data were calibrated with the most recent gain maps at the time of reduction. Pile-up was not an issue even for the brightest sources and no correction has been applied. Sources were detected using the "Mexican-Hat" wavelet detection routine WAVDETECT in CIAO in an 0.3–6.0 keV band image.

Count rates were converted into fluxes using a $\Gamma = 2$ power law model, a value typical for high flux sources in early-type galaxies (Irwin et al. 2003). We also assumed Galactic hydrogen column densities from Dickey & Lockman (1990). We considered fitting the spectrum of each individual ULX in order to derive a flux for each source, but our main goal was to compare the number of detected high flux sources to the number of sources predicted from deep field studies. Since previous deep field studies have assumed a single power law model to convert counts to flux, we have done the same. All X-ray luminosities are quoted in the 0.3–10 keV range unless noted otherwise.

Depending on the angular size of the galaxy, from five to 16 effective (half-light) radii would fit at least partially on the ACIS-S chip. For each ULX candidate, its projected position within the galaxy as a function of effective radii was noted (e.g., between 0–1 effective radii, between 1–2 effective radii, etc.), where the effective radius for each galaxy has been collected from the literature. This was done in order to create a combined radial profile for the ULX candidates to determine their spatial distribution. In a future paper, we will catalog the positions, count rates, spectral parameters, and other relevant information of the ULX candidates presented here.

3. RESULTS

3.1. *The Number of Expected Foreground/Background Sources*

To determine the number of unrelated foreground/background X-ray sources expected in the field of view of each observation, the log N vs. log S_X relation derived by Hasinger et al. (1998) was employed. We considered using one of the *Chandra* deep field studies (i.e., Giacconi et al. 2001), but the number of very high flux sources found within a typical *Chandra* field of view is so small that the slope of the log N vs. log S_X relation at the high flux end is poorly constrained, and would lead to poorly constrained values for the expected number of high flux sources. Conversely, the *ROSAT* HRI-derived log N

vs. log S_X relation of Hasinger et al. (1998) was determined from both a deep observation of the Lockman Hole and many shorter pointed observations of isolated, non-extended X-ray sources in order to sufficiently populate the high flux end of the log N vs. log S_X relation.

The log N vs. log S_X relation given in Hasinger et al. (1998) is (upon integrating the differential form):

$$N(> S_X) = \begin{cases} 117.0\ S_X^{-0.94} - 20.1 & S_X < 2.66 \\ 138.4\ S_X^{-1.72} + 0.87 & S_X > 2.66 \end{cases}, \tag{1}$$

where $N(> S_X)$ is the number of sources with fluxes exceeding S_X per square degree, and S_X is the 0.5–2.0 keV flux of the source in units of 10^{-14} ergs s^{-1} cm^{-2}. For each of the 28 *Chandra* fields, we calculated the number of expected background/foreground sources with 0.5–2.0 keV fluxes corresponding to 0.3–10 keV luminosities of $1-2\times10^{39}$ ergs s^{-1} and $> 2\times10^{39}$ ergs s^{-1} (if the sources are assumed to be at the distance of the target galaxy). In total, 33.1 and 33.5 sources were expected in the 28 *Chandra* fields that would be mistaken as $1-2\times10^{39}$ ergs s^{-1} and $> 2\times10^{39}$ ergs s^{-1} sources, respectively. The number of such sources actually detected was $75^{+9.7}_{-8.6}$ and $31^{+6.6}_{-5.5}$, respectively, where the errors given are 1σ Poisson uncertainties. So while there is a significant excess in the number of $1-2\times10^{39}$ ergs s^{-1} sources over what was expected, the number of $> 2\times10^{39}$ ergs s^{-1} sources detected is precisely what is predicted from deep field studies.

3.2. *The Spatial Distribution of the High Flux Sources*

In addition to comparing the number of foreground/background sources expected to the number of ULX candidates in the galaxies, the distribution of the sources can provide an independent estimate of the amount of contamination from foreground/background objects. We created one combined radial distribution profile of all the sources in the sample, as discussed above. In order to improve the statistics, the 16 original radial bins were grouped into five larger bins: 0–1, 1–2, 2–3, 3–7, and 7–16 effective radii. The number of ULX candidates in each bin was divided by the area of the bin in units of the effective area. This was done so that a random distribution of sources would yield a flat radial profile, while a distribution that followed the optical light of the galaxy would be significantly peaked toward the center. The combined radial profile is shown in Figure 1. We have plotted the distributions for the $1-2\times10^{39}$ ergs s^{-1} and $> 2\times10^{39}$ ergs s^{-1} sources separately. At large radii, the profiles of both luminosity classes are flat, indicative of a distribution that is randomly distributed. Within two effective radii, there is a clear peak in the profile of the $1-2\times10^{39}$ ergs s^{-1} sources. Of the 19 sources found within one effective radius, only 1.6 are expected to be foreground/background contaminants, indicating that most of the sources belong to the galaxies in the sample. Such a strong peak is not seen in the radial profile of the $> 2\times10^{39}$ ergs s^{-1} sources. While there is a slight overabundance of $> 2\times10^{39}$ ergs s^{-1} sources within one effective radius (four were detected while 1.7 were expected), this overabundance is only significant at the 90% confidence level. Furthermore, of the four $> 2\times10^{39}$ ergs s^{-1} sources within one effective radius, three have luminosities below 2.4×10^{39} ergs s^{-1}. Thus, even if these three sources do belong to the galaxies they are only minimally above the 2×10^{39} ergs s^{-1} threshold, and would fall below this threshold if their host galaxies were only 8% closer than was assumed. Finally, for two of the three sources, fitting their spectra (rather than assuming a $\Gamma = 2$ spectral model) yielded luminosities less than 2.2×10^{39} ergs s^{-1} for these two sources.

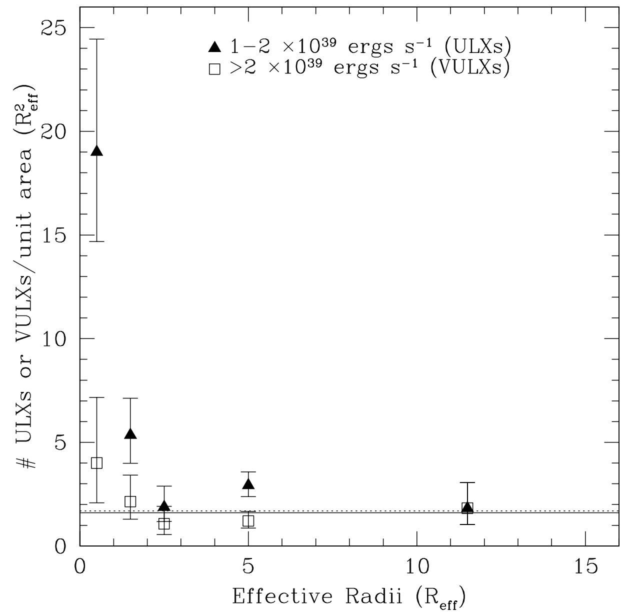

FIG. 1.— Composite radial profiles of sources with apparent luminosities of $1-2\times10^{39}$ ergs s^{-1} (*filled triangles*) and $> 2\times10^{39}$ ergs s^{-1} sources (*open squares*) normalized by the area of each spatial bin for all sources within the 28 galaxies of our sample. Errors are 1σ. The solid and dotted lines represent the expected radial distribution of unrelated background/foreground sources for the two luminosity classes.

3.3. *Comparison to the Colbert & Ptak (2002) VULX Catalog*

Colbert & Ptak (2002) analyzed 15 early-type and 39 late-type galaxies observed with the *ROSAT* HRI and found a total of 87 ULX candidates. There is some overlap between the early-type galaxies in their sample and ours, and in general they surveyed out to approximately the same radial distance as we have. Colbert & Ptak (2002) scaled the galaxies by R_{25} rather than the effective radius (R_{25} is typically 3–5 times larger than the effective radius), and included in their catalog all sources with 2–10 keV luminosities greater than 10^{39} ergs s^{-1} within twice the R_{25} contour (or approximately 6–10 effective radii). Since not all of the observations were complete down to 10^{39} ergs s^{-1}, it is not possible to compare the expected number of foreground/background sources to the number of ULX candidates found, but it is possible to look at the spatial distribution of the ULX candidates. Colbert & Ptak (2002) assumed a power law of $\Gamma = 1.7$ rather than the $\Gamma = 2.0$ model used in our work. After accounting for the difference in spectral model choice and energy band, it was found that the lower luminosity limit of their catalog was L_X (0.3–10 keV) $\sim 2\times10^{39}$ ergs s^{-1} (they are all what we would call VULXs). Based on the results of § 3.1 and § 3.2, we would therefore expect the distribution of their sources to be consistent with a random distribution.

From Table 1 of Colbert & Ptak (2002), we determined how many VULX candidates were within radial bins of 0–0.5 R_{25}, 0.5–1.0 R_{25}, 1.0–1.5 R_{25}, and 1.5–2.0 R_{25}. We included any high X-ray flux QSOs that were excluded by Colbert & Ptak (2002), and excluded a VULX candidate in NGC 4374 (IXO 50) for which *Chandra* images showed it to be a clump of hot gas rather than a point source. We also excluded from the sample any galaxy for which twice R_{25} exceeded $17'$ since the outer radial bins would not fit within the *ROSAT* HRI field of view.

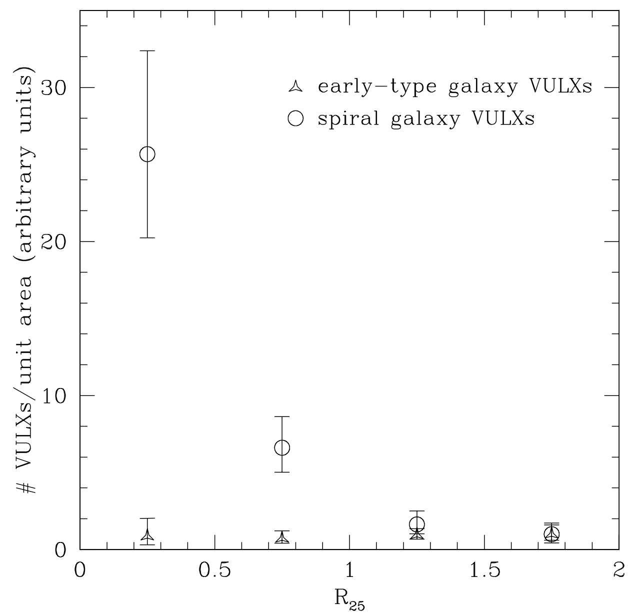

Fig. 2.— Composite radial profiles of VULXs compiled by Colbert & Ptak (2002) for early-type galaxies and spiral galaxies normalized by the area of each spatial bin. The bins have been renormalized such that the fourth spatial bin of each profile has a value of 1.0. Errors are 1σ.

For a random distribution, we would expect the number of sources detected within each radial bin to scale simply with the ratio of the areas of the four bins. For 0–0.5 R_{25}, 0.5–1.0 R_{25}, 1.0–1.5 R_{25}, and 1.5–2.0 R_{25} bins, this would be a 1:3:5:7 ratio. The number of VULX candidates found in these four bins were 2, 5, 11, and 16, respectively. Within the Poisson uncertainties, the distribution of the VULX candidates are completely consistent with being random (and therefore unrelated to the galaxies). Interestingly, a similar exercise with late-type galaxies in the Colbert & Ptak (2002) catalog yields a completely different result; within the four radial bins there were 22, 17, 7, and 6 VULX candidates, respectively. The sources are heavily concentrated toward the centers of the galaxies, indicating that nearly all of the sources within R_{25} are bona fide VULXs. This is not surprising given the well-known connection between recent star formation and the presence of VULXs. The results for both the early-type and spiral galaxy samples are illustrated in Figure 2, where the VULX distributions for the two samples have both been normalized to 1.0 in the fourth spatial bin for easier comparison.

3.4. *Two VULXs Within Globular Clusters of NGC 1399*

Angelini, Loewenstein, & Mushotzky (2001) found that two sources with $L_X > 2 \times 10^{39}$ ergs s^{-1} were coincident with globular cluster candidates, which would conflict with the idea that sources this luminous avoid early-type systems. We located these two sources in the *Chandra* data of NGC 1399. The spectrum of one of the sources was very soft ($\Gamma = 2.5$), and with this spectral model we determined its X-ray luminosity to be 2.3 $(d/20\ \mathrm{Mpc})^2 \times 10^{39}$ ergs s^{-1}. Thus, if NGC 1399 is only 8% closer (within the uncertainties of the Tonry et al. 2001 distance estimate), the luminosity of this source would drop below 2×10^{39} ergs s^{-1}. The other source has a considerably higher luminosity ($L_X = 4.7 \times 10^{39}$ ergs s^{-1}) and cannot be explained by assuming a slightly smaller distance. It is possible that the optical counterpart is really a background AGN that has been miss-identified as a globular cluster. We have analyzed the same *HST* data that Angelini et al. (2001) used to obtain a globular cluster list for this galaxy, and have verified that the object has a globular cluster-like $B - I$ color and apparent magnitude. However, at the distance of NGC 1399, a globular cluster would be at best marginally-resolved by *HST*, so only a high resolution spectrum of the optical counterpart will unambiguously determine if it is a globular cluster or an AGN. At any rate, given the large number of globular clusters that NGC 1399 contains, as well as the large number of globular clusters in our sample as a whole, we can at least conclude that $> 2 \times 10^{39}$ ergs s^{-1} sources are extremely rare in globular clusters, and in early-type systems in general.

4. A STANDARD DEFINITION FOR AN ULTRALUMINOUS X-RAY SOURCE

There does not appear to be a standard definition for a ULX in the literature. Various studies have defined ULXs differently, using different luminosity thresholds and different energy bands. Here, we propose that a ULX be defined as having a 0.3–10 keV luminosity that exceeds 2×10^{39} ergs s^{-1} (what we have been calling VULXs in this paper). Using 2×10^{39} ergs s^{-1} as a break between ULXs and normal X-ray binaries has two advantages. First, we note that X-ray sources that have luminosities of $1 - 2 \times 10^{39}$ ergs s^{-1} can be adequately explained by accretion onto a 10–20 $M_\odot$ black hole (for which observational evidence already exists for blacks holes of this mass in our own Galaxy, e.g, Cygnus X-1), thus eliminating the need for a more exotic explanation such as beaming or the existence of intermediate mass black holes. Second, $> 2 \times 10^{39}$ ergs s^{-1} sources are apparently lacking (or at least very rare) in old stellar populations, suggesting that an additional class of object is present in late-type galaxies that is absent in early-type galaxies.

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REFERENCES

Angelini, L., Loewenstein, M., & Mushotzky, R. F. 2001, ApJ, 557, L35

Begelman, M. C. 2002, ApJ, 568, L97

Colbert, E. J. M., & Mushozky, R. F. 1999, ApJ, 519, 89

Colbert, E. J. M., & Ptak, A. F. 2002, ApJS, 143, 25

Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215

Fabbiano, G. 1989, ARA&A, 27, 87

Giacconi, R., Rosati, P., Tozzi, P., Nonino, M., Hasinger, G., Norman, C., Bergeron, J., Borgani, S., Gilli, R., Gilmozzi, R., & Zheng, W. 2001, ApJ, 551, 624

Hasinger, G., Burg, R., Giacconi, R., Schmidt, M., Trumper, J., & Zamorani, G. 1998, A&A, 329, 482

Irwin, J. A., Athey, A. E., & Bregman, J. N. 2003, ApJ, 587, 356

King, A. R., Davies, M. B., Ward, M. J., Fabbiano, G., & Elvis, M. 2001, ApJ, 552, L109

Makishima, K., et al. 2000, ApJ, 535, 632

Miller, J. M., Fabbiano, G., Miller, M. C., & Fabian, A. C. 2003, ApJ, 585, L37

Miller, M. C., & Hamilton, D. P. 2002, MNRAS, 330, 232

Mei, S., Kissler-Patig, M., Silva, D. R., & Quinn, P. J. 2001, A&A, 376, 793

Perrett K. M., Hanes, D. A., Butterworth, S. T., Kavelaars, Jj, Geisler, D., Harris, W. E. 1997, AJ, 113, 895

Roberts, T. P., & Warwick, R. S. 2000, MNRAS, 315, 98

Roberts, T. P., Warwick, R. S., Ward, M. J., & Murray, S. S. 2002, MNRAS, 337, 677

Tonry, J. L., Dressler, A., Blakeslee, J. P., Ajhar, E. A., Fletcher, A. B., Luppino, G. A., Metzger, M. R., & Moore, C. B. 2001, ApJ, 546, 681

Zezas, A., & Fabbiano, G. 2002, ApJ, 577, 726